Development of Standards for Stand-off Distances and Blast Walls for Force Protection

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The threat to our operational forces and facilities (both within U.S. and abroad) in die year 2000 and beyond is posed by major advances in weapons systems and technology and the increasing sophistication of terrorist weapons. The availability of high technology weapons to more and more nations and terrorists makes it critical that we develop advanced protective construction technology. The Services specially need technology in conjunction with high-performance computing that will permit hardened facilities to be designed and constructed confidently and cost effectively. In addition to the design of facilities, guidance is also required on stand-off distances, construction of blast walls, and hardening of structures against terrorist activities both within the country and abroad. Hence, the overall goal of this project is to develop standards for stand-off distances and design of blast walls for survivable bases and facilities.

To address the Force Protection problems, DoD in collaboration with the Justice Department is conducting a small number of experiments over the next couple of years. Due to complex nature of the phenomena, experimentation alone will not provide all the information required to develop standards for stand-off distances and blast wall designs. Further, experiments and full-scale tests are prohibitively expensive to study the design variables. Hence, High-performance computing simulations with precise experiments and validated numerical constitutive material models are the only way to develop reliable prediction procedures for developing the standards for stand-off distances. The technical approach consists of conducting pre-experiment simulations first on scalable computers to provide ranges for gauges and specified location of gauges for all the experimental layouts. Next, based on precise experiment results, develop and/or enhance numerical algorithms and material constitutive models implemented in the DoD CHSSI CSM scalable software. Finally, develop standards for stand-off distances and design blast resistant walls using validated numerical tools to meet the Force Protection needs.

This is a computational RDT&E effort to enhance Force protection. Simulation of these events with validated numerical constitutive models will advance the technology of protective structures. Due to the complexities involved these experiments have to be performed on scalable computers because conventional simplified design methods are inadequate and inaccurate. These design studies will assist Services to establish threat based stand-off or exclusion areas around compounds and bases. Further, these design studies will enhance the design of barriers or blast walls to shield or protect vulnerable compounds and structures and advanced protective construction technology. In his recent report [1] to the President and Congress, Honorable William J. Perry wrote, “I have designated the Under Secretary of Defense for Acquisition and Technology as responsible for antiterrorism technology development and asked him to expedite the adoption of new advanced technologies to meet force protection needs.” The proposed research is in direct support of the above activity.

2. Introduction

The Survivability and Protective Structures (S&PS) research program is focused on die warfighter's needs for force protection. FORCE XXI and the Army After Next will be much smaller and have to react quickly to events anywhere in the world. In the execution of its missions the Army will be challenged by increasingly advanced conventional and terrorist weapons threats which will be readily available to many of the nations in the world. These weapons threats cover the entire spectrum from small arms, indirect fires, vehicle bombs, advanced entry devices, smart or guided conventional weapons, and robust penetrating munitions. The threat from terrorist or saboteur weapons must be countered during peacetime as well as during military operations. The ability to determine weapons effects and predict the survivability of protective structures are essential for survival of the smaller Army.

Waterways Experiment Station (WES) is actively involved in developing precise experiments and computational tools to assist DoD in developing standards to address Force Protection needs. For example, during 1996, WES in collaboration with DSWA conducted a phenomenology experiment to understand truck bomb explosion at Fort Polk. Due to the complex nature of this problem, validated numerical simulation of the experiment helped DoD to understand the phenomena of truck bomb explosion in the presence of water tamping better. All the processors and all the memory on the DoD MSRC vector computer C90 were utilized to perform this three-dimensional numerical simulation. In addition to the Fort Polk experiment simulations, WES performed large scale numerical simulations of Khobar Towers terrorist alternate scenario at Saudi Arabia.
Subsequently some of these findings were documented in the Appendix C of William Perry's report to the President and Congress on Force Protection. Recently, VVES in collaboration with DSWA performed numerical simulations to assist base commanders at Saudi Arabia in determining stand-off distances for one of the base at Saudi Arabia. Under the 1997–98 DoD HPC challenge project, WES is developing truck bomb weapons effects database for DoD by using validated computational tools and couple of experiments [5,6].

Stand-off distances will be addressed during the first year under HPC challenge project. This project will initially perform validation of numerical models implemented into the codes, namely, concrete, steel, and geologic materials against available experimental results. Modeling and analysis will be performed on different threats and various configurations of blast wall designs. These design studies will assist Services to establish threat based stand-off or exclusion areas around compounds and bases. Further, these design studies will enhance the design of barriers or blast walls to shield or protect vulnerable compounds and structures. These problems are three-dimensional, highly nonlinear, and involve complex interactions of various materials. Hence, three-dimensional simulations may require solving millions of equations to adequately model the physical phenomena and the interaction of complex system of components.

Scalable computers have to be utilized to solve these types three-dimensional problems because of the tremendous memory and processor speed requirements. Small three-dimensional problems for components can be analyzed on conventional supercomputers. However, to analyze the above large three-dimensional problems, much more memory and processor speed are needed. For example, memory requirement goes by a factor of eight if mesh size is halved. Typically, the codes are based on explicit time integration method so the time step scales with the mesh size. That is, if mesh is halved then the time step is cut in halve. The CPU requirements go up as the fourth power of mesh size. Note that CPU requirement increases faster than the memory requirements. Hence, scalable computing is the only solution to analyze practical three-dimensional problems.

3. Justification/DoD Relevance

The U.S. Army Engineer Waterways Experiment Station (WES) is the lead laboratory for research in civil engineering area of Survivability and Protective Structures (S&PS) [2] under the Tri-Service Project Reliance Civil engineering Science and Technology Plan. The S&PS research program is focused on the warfighter's needs for force protection. FORCE XXI and the Army After Next will be much smaller and have to react quickly to events anywhere in the world. In the execution of its missions the Army will be challenged by increasingly advanced conventional and terrorist weapons threats which will be readily available to many of the nations in the world. These weapons threats cover the entire spectrum from small arms, indirect fires, vehicle bombs, advanced entry devices, smart or guided conventional weapons, and robust penetrating munitions. 'Me threat from terrorist or saboteur weapons must be countered during peacetime as well as during military operations. The ability to determine weapons effects and predict the survivability of protective structures are essential for survival of the smaller Army.

This is a computational RDT&E effort to enhance Force protection. Simulation of these events with validated numerical constitutive models will advance the technology of protective structures. Due to the complexities involved these numerical experiments have to be performed on scalable computers because conventional simplified design methods are inadequate and inaccurate. These design studies will assist Services to establish threat based stand-off or exclusion areas around compounds and bases. Further, these design studies will enhance the design of barriers or blast walls to shield or protect vulnerable compounds and structures and advanced protective construction technology. In his recent report [1] to the President and Congress, Honorable William J. Perry wrote, “I have designated the Under Secretary of Defense for Acquisition and Technology as responsible for antiterrorism technology development and asked him to expedite the adoption of new advanced technologies to meet force protection needs.” The proposed research is in direct support of the above activity.

4. Technical Approach

4.1 Objective

To overall objective is to develop standards for stand-off distances and blast walls, and anti-terrorism planner to the base commanders. These standards and planners will assist base commanders to assess the vulnerability of their facilities and take appropriate measures to protect their forces form terrorist/saboteur attack. The problems associated in developing standards and anti-terrorism planners are intrinsically three-dimensional, highly nonlinear, and involve complex interactions of various materials. Due to the complex phenomena, experimentation will not provide all the information required for addressing the above objective. High-performance computing simulations with precise experiments is the only way to understand the fundamental behavior of the weapons effects and its effect on structures. Three-dimensional simulations may require solving millions of equations to adequately model the physical phenomena and the interaction of complex system of components. To address the above objective, this challenge project will perform following numerical simulation studies on scalable computers:

Standards for stand-off distances for various threats.
(a) Design of blast walls.
(b) Effect of blast walls due to explosions.

Challenge Project Team

Some of the key DoD and DoE players who will be working on this HPC challenge project are:
Dr. Jimmy P. Balsara, CEVVES
(1) Dr. Raju R. Namburu, CEWES
Dr. Photios Papados, CEWES
Dr. Chuck Weiss, CEWES
Mr. Tommy Bevins, CEWES
Mr. Byron Armstong, CEWES
Dr. Gene Hertel, Sandia National Laboratory
Dr. Carol Hoover, Lawrence Livermore National Laboratory

4.3 Schedule

Weapons effects databases and HPC simulations developed under Khobar Towers Bomb Damage and Water Tamping Studies DoD HPC challenge project will be used in this study. The plan and estimated milestones for the project for FY98, FY99 and FY00 to achieve the objectives of the proposed project are discussed below.

The following tasks will be addressed during the FY98. These simulations will assist in validating software for stand-off distances.

FY98 Pre-experiment simulations of stand-off distance experiments.
Validation of constitutive material models.
Comparison of simulations with experiments.

Validation computational model for stand-off distances from FY98 activity and weapons effects database from "Khobar Towers Bomb Damage Water Tamping Studies," DoD HPC challenge project will be used to develop optimum design of blast walls during FY99. Tasks involved during this period of study are:

FY99 Design of blast walls against various threats. Develop standards for blast wall designs.

Activity in the FY00 will be geared towards development of standards for stand-off distances with blast walls against terrorist threats.

FY00 Optimum stand-off distance with blast wall. Develop standards for stand-off distances.

4.4 Computational Methodology

Multidimensional computer codes with sophisticated material models are required to realistically model this class shock wave physics and large deformation structural response problems. The important class of shock wave physics problems is characterized by large deformations. These problems involve penetration, perforation, fragmentation, high-explosive initiation and detonation, and high velocity impact. Further, these problems are intrinsically three-dimensional and involve complex interactions of materials, including, alloys, concrete, geologic materials and energetic materials. Further, the software must model the multiphase (solid-liquid-vapor), strength, fracture, and high-explosive detonation properties of these materials. The software developed under CHSSI CSM CTA, namely, Large deformation and Shock physics projects along with recently developed numerical constitutive material models under very high strain-rates will be used to perform numerical simulations.

DoD in collaboration with Lawrence Livermore National Laboratory is developing parallel DYNA3D software [3] under CHSSI CSM large defori-nation project. Vector version of the DYNA3D computer program set the world's standard for three-dimensional nonlinear finite element structural dynamic codes. DYNA3D provides a numerical solution of the continuum equations in Lagrangian coordinates using adiabatic approximations. The large deformation strain-rate based continuum equations are solved using a finite element treatment for the spatial derivatives and an explicit, central difference time integration method. The solution employs an element-by-element technique so that matrix inversion is not necessary. The DYNA3D scalable algorithms are designed to divide the problem mesh into sub domains. Solutions on sub domains are connected together by communicating data across processors along the boundaries of the sub domains. Load and communication balancing algorithms assign elements (continuum, shell, and beam) to one processor uniquely, and nodes to any processor owning connected element. Consequently, nodes on processor boundaries, shared nodes, are stored in more than one processor. Boundary node lists are grouped by target processor so only one send per processor time step need be executed for each other processor with which a given processor interacts. The decoupled time integration for the nodal coordinates is duplicated for the shared nodes. The motion for shared nodes is duplicated identically by adding a communication step after the nodal forces are calculated. The nodal force is a sum of contributions from applied loads, element deformations, contact-restoring forces, and other boundary conditions.

DoD in collaboration with Sandia National Laboratory is developing parallel version of CTH shock physics code[4]. The parallel CTH is a multi-dimensional, multi-material, finite-volume shock physics code that models shocks, and the multiphase behavior, strength, and fracture of materials. The equations governing the conservation of mass, momentum and energy are integrated explicitly in time using two-step Eulerian scheme. The first step is a Lagrangian step in which computational cells distort to follow the material motion, using an algorithm which is second-order accurate in space and time. The second step is an advection step in which the distorted cells are mapped back to the Eulerian mesh. The global mesh is mapped to the nodes on each processor by dividing it into blocks in such a way that each node has nearly same number of mesh points. When a block of the global mesh is mapped to a node, it is surrounded by a layer of ghost cells. These cells are used for enforcing physical boundary conditions when the block boundary corresponds to a physical boundary or for communicating results from logically adjacent nodes when block boundary falls In the interior of the simulation domain.

Eulerian software will be used first to model various configurations for stand-off distances including blast walls. Eulerian and Lagrangian tracers will be used in Eulerian software to obtain time-history at different locations in the problem domain. Next, timehistory data will be used to study the blast effects on structure in more detail including brittle material failure mechanisms.

4.5 Software's Efficiency

The scalable software developed under CHSSI CSM CTA, namely, Shock Physics and Large Deformation will be used. Both these software are currently running oil Cray T3E and IBM SP under batch environment for solving FY97 challenge project problems. Scalability Studies performed for shock physics and large deformation projects are shown in the following figures.

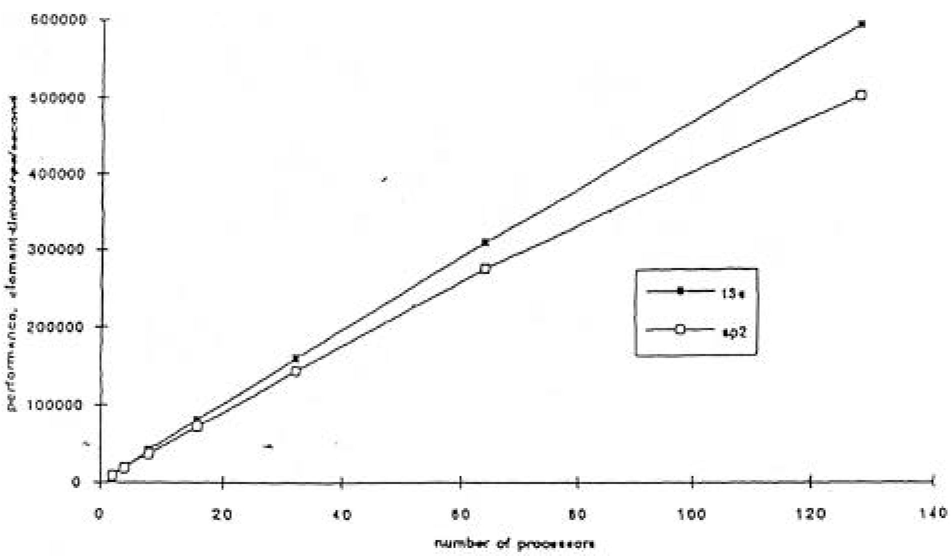

Figure 1. Performance studies of ParaDyna for a typical DoD application.

5. Required Resources and Justification

Typical size of each computational run for FY98 is given in the following table:

	Eulerain	Larangian
Number of cells/elements	40E+06 to 60E+06	2E+06 to 5E+06
Number of materials	4	5
Number of runs	25	20

Based on our past experience, to solve 18 E+06 Eulerian equations with 4 materials it took about 9,600 processor hours on Cray T3E. Similarly, for solving 1 E+06 Lagrangian equations, with 4 materials it took about 1,200 processor hours on Cray T3E. Based on the performance studies of the software it takes little bit longer to solve above problem on IBM SP than on Cray T3E. The estimates shown in tables under summary section are projections of the above discussed runs.

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6. Summary Sheet

Section I: Principal Investigator/Project Leader Identification

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Section II: Resources Requirement

FY98

Platform(s)	Location		Resources (processor-hours)	
	First	Second	Request	Minimum
IBM SP2	CEWES	ASC	300,000	300,000
Cray T3E	CEWES		100,000	100,000
C90/T90	CEWES	ARL	10,000	5,000
Origin 2000	CEWES		50,000	50,000

	Typical Job	Maximum Job	Typical Job	Maximum Job
IBM SP	50	200	100	300
Cray T3E	10	30	50	100
C-90/T-90	1	2	40	80
Origin 2000	2	10	20	40

FY99

Platform(s)	Location		Resources (processor-hours)	
	First	Second	Request	Minimum
IBM SP2	CEWES	ASC	600,000	600,000
Cray T3E	CEWES		200,000	200,000
C90/T90	CEWES	ARL	10,000	5,000
Origin 2000	CEWES		100,000	100,000

	Typical Job	Maximum Job	Typical Job	Maximum Job
IBM SP	50	300	100	400
Cray T3E	10	60	50	150
C90/T90	1	2	40	80
Origin 2000	2	10	20	80

FY00

Platform(s)	Location		Resources (processor-hours)	
	First	Second	Request	Minimum
IBM SP2	CEWES	ASC	900,000	900,000
Cray T3E	CEWES		600,000	600,000
C90/T90	CEWES	ARL	10,000	5,000
Origin 2000	CEWES		100,000	50,000

	Typical Job	Maximum Job	Typical Job	Maximum Job
IBM SP	50	300	100	300
Cray T3E	10	60	50	100
C90/T90	1	2	40	80
Origin 2000	2	10	20	40

Section III: Project Summary

DoD Challenge Project Title: Development of Standards for Stand-Off Distance and Blast Walls for Force Protection Related Requirements Project Title(s): Survivability and Protective Structures Requirements Project Number(s):

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Areas of Research Experience

Computational mechanics; Structural dynamics; Shock physics; Finite element methods; Parallel computational methods; Contact-impact; Ballistic shock waves; Penetration; Computational heat transfer; Adaptive techniques; Composite structures; Structural optimization; Computational methods for manufacturing; Algorithms for interdisciplinary thermal-structural-fluid problems; and Mechanical design.

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Organization of Professional Meetings

Symposium on High-performance Computing in Computational Structural Mechanics, at the United States Association for Computational Mechanics, San Francisco, CA, Aug. 1997.

Symposium on Recent Advances in DoD Applications in Structural Mechanics, at the McNU97 conference, Evanston, IL, July 1997.

Symposium on Computational Methods for Thermal-Structural Problems, at the 2nd International Conference on Thermal Stresses, Rochester, NY, June 1997.

Workshop on High-Performance Computing in Structural Mechanics, sponsored by ARO/CEWES/DSWA/DoD HPC MSRC at CEWES, Vicksburg, MS, April 96.

Workshop on High Performance Computing and Structural Dynamics, sponsored by TARDEC/ARO/AHPCRC, Warren, MI, 1993.

1992 ASME Winter Annual Meeting, Computers in Engineering Division, Session on Advanced Topics in Finite Element Methods, Nov., 1992.

1994 ASME Winter Annual Meeting, Computers in Engineering Division, Organizing a Symposium on Structural Dynamics on High Performance Computing, Nov., 1994.

Honors/Awards/Commendations

Nominated for technical excellence by the Systems Engineering Division, Computer Sciences Corporation, 1994.

Letter of commendation from the Chief, PM Abrams Tank system, U S Army Tank-Automotive Command for saving Army funds by modeling and simulation, 1993.

Top of the graduating class (M.S.), 1980 at Andhra University, India

Fellowship form Minnesota Supercomputer Center, Minneapolis, MN, 1988.

Affiliations

American Society of Mechanical Engineers

American Institute of Aeronautics and Astronautics

United States Association for Computational Mechanics

International Association for Computational Mechanics

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Research Experience

Dr. Jimmy P. Balsara is a senior research civil engineer in the Structures Laboratory at the U.S. Army Engineer Waterways Experiment Station (WES). He provides technical guidance for the Survivability and Protective Structures program at WES. He joined WES in 1966 as a project engineer in the Nuclear Weapons Effects Division where he conducted research on the response of structures to blast and shock. In 1984, he became the Chief of the Structural Mechanics Division, Structures Laboratory where he directed research pertaining to the dynamic response of structures to blast and shock from conventional and nuclear weapons, and seismic effects on hydraulic structures. In 1994, he became the Chief of the Geomechanics and Explosion Effects Division where he directed research on material characterization under dynamic loads and in the phenomenology of explosion effects.

RECENT PUBLICATIONS OF PRESENTATIONS

Balsara, J.P., Rohani, B., and Coltharp, D.R. April 1992. Army Research and Development in Conventional Weapons Effects on Survivability and Protective Structures, Published in the Special Edition of Nuclear Technology Transfer and Conventional Force Applications, Nuclear Survivability, Defense Nuclear Agency.

Coltharp, D.R. Rohani B., and Balsara, J.P. April 1992. Conventional Weapons Effects on Protective Structures, published in The Special Edition of Nuclear Technology Transfer and Conventional Force Applications, Nuclear Survivability, Defense Nuclear Agency.

Balsara, J.P. and Namburu, R.R. February 1997. "Khobar Towers Bomb Damage Simulations," DOD ST Conference on Modeling and Simulation, Washington, DC.

Balsara, J.P. and Namburu, R. June-July 1997. "Recent Developments in Computational Structural Mechanics Relating to Survivability and Protective Structures," McNU '97 Conference, Chicago, IL.

Namburu, R.R., Balsara, J.P., and Bevins, T.L. August 1997. 'Large-Scale Explicit Computations in Structural Mechanics," 411 U.S. National Congress on Computational Mechanics, San Francisco.

Balsara, J.P., Namburu, R.R., and Bevins, T.L. September 1997. "Effects of Water Tamping on Airblast and Cratering from an Above-Ground Cylindrical Charge," 151 International Symposium on the Military Aspects of Blast and Shock, Banff, Alberta, Canada.

INVITED TALKS

Balsara, J.P. and Namburu, R.R. March 3d, 1997. "Computational Structural Mechanics Relating to Survivability and Protective Structures," presented at the University of Illinois Urbana-Champaign Civil Engineering Lecture Series.

Balsara, J.P., and Namburu, R.R. April 3d, 1997. "High-Performance Computing Activities in Computational Structural Mechanics at CEWES," presented at the Science Research Center Seminar Series, Clark-Atlanta University.

HONORS/AWARDS

Dr. Balsara is the recipient of numerous honors and awards including the Department of the Army Meritorious Civilian Service Award (three times) and the Department of the Army Research and Development Achievement Award. In 1993, he was inducted into the Academy of Distinguished Alumni of Mechanical Engineering and Mechanics at West Virginia University.

PUBLISHED WORKS BY DR. JIMMY P. BALSARA

In addition to the following list of publications prepared by Dr. Jimmy P. Balsara, numerous technical reports and journal articles have been prepared and published by the staff under his supervision.

Papers published in proceedings of professional meetings are as follows:

Balsara, Jimmy P. 30 September through 4 October 1968. "Blast-Loaded Buried Arches," Journal of the Engineering Mechanics Division, ASCE, VOL 96, February 1970. Presented by author at ASCE Annual Meeting, Pittsburgh, PA.

Balsara, J.P. and Cummins, R.S., Jr. 30 September through 4 October 19G8. "Pressure Distribution of a Buried Flat Plate Subjected to Static and Airblast Overpressure." Paper presented at the ASCE Structural Engineering Meeting held at Pittsburgh, PA, Meeting Preprint 714.

Balsara, J.P. April 1967. "Model study of Blast-Loaded Buried Arches, 11 Technical paper prepared for the meeting of Panel N-2 TTCP, London.

Balsara, J.P. and Roggenkamp, L. April 1970. "Similitude Study of Reinforced Concrete Deep Beams." Presented by author at ASCE Annual Meeting, Portland, OR.

Balsara, J.P. and Walker, R.E. April 1973. "Analysis of an 80-foot Aircraft Shelter for Construction Stresses." Presented by coauthor at ASCE Annual Meeting, San Francisco, CA.

Balsara, J. P., and Fowler, J. 1973. "Vibration Tests of North Fork Dam Model." Fifth World Conference on Earthquake Engineering, Rome.

Balsara, J. P. May 1973. "Vibration Characteristics of the North Fork Dam, 11 5th Joint meeting of the U.S.-Japan Panel of Wind and Seismic Effects.

Balsara, J. P. May 1973. Silo Interaction Study (U)," Defense Nuclear Agency Long-Range Planning meeting (SECRET) Presented by author.

Balsara, J. P., and Norman, C. D. 1975. "Vibration Tests and Analysis of a Model Arch Dam, 11 Earthquake Engineering and Structural Dynamics Journal, Vol 4.

Balsara, J.P. 8–10 February 1977. "Response of Surface and near Surface Structures," Defense Nuclear Agency Strategic Structures Division Biennial Review Conference.

Flathau, W. J. and Balsara, J. P. 17–20 May 1978. "Soil Structure Interaction - An Overview," Proceedings of the Conference on Earth-Covered Settlements, Fort Worth, TX.

Kiger, S. A., and Balsara, J. P. "Response of Shallow Buried structures to Blast Loads," Proceedings of the 1978 ArmV Science Conference.

Kiger, S. A. and Balsara, J. P. 14–16 November 1978. "Results of Recent Hardened Structures Research," Proceedings of the Federal Republic of Germany's 100th Symposium on Weapons Effects on Protective Structures."

Balsara, J. P. and Crawford, J. 20-22 March 1979. "Bridge Tests," Defense Nuclear Agency Strategic Structures Division Biennial Review Conference.

Balsara, J. P. 4–6 May 1982. 11structural Tests," Session V Land-Based Systems, Defense Nuclear Agency Strategic Structures Division Review Conference.

Ball, J. W., and Balsara, J. P. October 1982. "Vulnerability of Steel Girder Bridges to Airblast," Shock and Vibration Bulletin, Bulletin 52, Supplement 1.

Kiger, S. A. and J. P. Balsara. 10–19 May 1983. "A Review of 1983 Revision of TM 5-855-1, Fundamentals of Protective Design (Nonnuclear) , " Symposium Proceedings, Part 2, The Interaction of Non-Nuclear Munitions with Structures (Distributed November 1983)

Kiger, S. A., Balsara, J. P., and Baylot, J. T. 1984, "A Computational Procedure for Peak In-Structure Motions and Shock Spectra for Conventional Weapons, " 54th Shock and Vibration Bulletin.

Technical Reports Published:

Balsara, J. P. and Cummins, R. S. October 1968. "Pressure Distribution on a Buried Flat Plate Subjected to Static and Airblast overpressures," MP N-G8-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hampe, P. A., and Balsara, J. P. July 1968. "An Experimental Study of Deep Beams," Report 1, MP N-68-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Balsara, J. P. January 1968. "Similitude Study of Flexible buried Arches Subjected to Blast Loads," Technical Report 1-807, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Albritton, G. E., Dalsara, J. P., and Bayer, D. M. November 1969. "Response of Two-Way Reinforced and Unreinforced Concrete Slabs to Static and Dynamic Loading," Report 4, Mine Shaft Series, Mine Under Event, Program 3, Structural Response, Deep Slabs Tests, Technical Report N-69-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Watt, J. M., Balsara, J. P., and Albritton, G. E. September 1970. "Response of Two-Way Reinforced and Unreinforced Concrete Slabs to Static to Static and Dynamic Loading," Report 6, Mine Shaft Series, Mineral Rock Event, Program 3, Structural Response Studies, Deep Slab Tests, Phase 2, Technical Report N-69-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Balsara, J. P., Walker, R. E., and Ball, J. W. October 1970. "Analysis and Tests of 1/6-Scale Models of Minuteman Launcher Equipment Room (U)," Technical Report N-70-13, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS (SECRET).

Balsara, J. P., and Walker, R. E. June 1971. "Static Test of 1/6-Scale Model Minuteman Launch Facility (U)," Technical Report N-71-5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS (SECRET).

Balsara, J. P. and Walker, R. E. March 1972. "Static Test of 1/6-Scale Model Minuteman Launch Closure (U)," Miscellaneous Paper N-72-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS (SECRET).

Balsara, J. P. and Roggenkamp, L. E. January 1971. "Similitude Study of Reinforced Concrete Deep Beams," Miscellaneous Paper N-71, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Balsara, J. P., et al. June 1972. "Army Aircraft Protective Structures Designs, Report 8, Analysis and Evaluation of a Large Hardened Arch Shelter," Technical Report N-69-8, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Balsara, J. P. and Walker R. E. December 1972. "State-of-the-Art Evaluation of Vulnerability and Hardness Analyses for BMD Facilities, Chapter 3, Airblast," Technical Report N-, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS (CONFIDENTIAL - FRD).

Balsara, J. P. and Hossley, J. R. December 1973. "Evaluation of the Safeguard System Perimeter Acquisition Radar Building Shear Key Connections," Technical Report N-73-9, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Balsara, J. P., Walker, R. E., and Fowler, J. March 1974. "Vibration Characteristics of the North Fork Dam Model," Technical

Report N-74-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Balsara, J. P. and Hartman, D. September 1975. "MIDDLE NORTH Series, MIXED COMPANY Event, Silo Interaction Study," Defense Nuclear Agency POR 6G17.

Cost, V. T., and Balsara, J. P. October 1978. "Fuel-Air Explosive Tests on Urban and Battlefield Structures (U) " Technical Report 78-6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS (CONFIDENTIAL).

Jones, P. S., Balsara, J. P., Albritton, G. E., Karagozian, J., and Isenburg, J. February 1984. "Silo Test Program (U); Dry Site Test 1 (DST-1), Structure VS1.5A (U)," Technical Report SL 84-3, Report 1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS (SECRET).

Jones, P. S., Balsara, J. P., Albritton, G. E., Karagozian, J., and Levine, H. S. February 1984. "Silo Test Program (U); Dry Site Test 2 (DST-2), Structure VS1.5C (U)," Technical Report SL84-3, Report 2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS (SECRET).

Jones, P. S., Balsara, J. P., Albritton, G. E., Karagozian, J., and Levine, H. S. February 1984. "Silo Test Program (U); Dry Site Test 3 (DST-3), Structure VS1.5A (U)," Technical Report SL84-3, Report 3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS(SECRET).

Jones, P. S., Balsara, J. P., Albritton, G. E., Karagozian, J., and Levine, H. S. March 1984. "Silo Test Program (U); Dry Site Test 4 and 5 (DST-4 and DST-5), Structure VS1. 5D (U)," Technical Report SL-84-3, Report 4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS (SECRET).

Shore, J. S., Jones, P. S., Balsara, J. P., Karagozian, J., and Levine, H. S. April 1985. "Silo Test Program (STP), Wet Site Test, Retest of Structure VS1.5B," Technical Report SL-84-3, Report 6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS (SECRET).

Hammons, M. I., Albritton, G. E., Balsara, J. P., Karagozian, J., and Chen, P. H. October 1986. "Hard Silo Component Test Program; Closure Component Static Tests," Technical Report SL-8612, Report 1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hammons, M. I., Albritton, G. E., Balsara, J. P., Karagozian J., Chen, P. H., and Wanchoo, M. K. October 1986. "Hard Silo Component Test Program; Addendum A to Closure Component Static

Tests," Technical Report SL-86-12, Report 2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hammons, M. I., Balsara, J. P., Albritton, G. E.,Johnson, W. G., Karagozian, J., Chen, P. H., and Wanchoo, M. K. January 1987 "Hard Silo Component Test Program; Closure Dynamic Test 1 (CDT-1),” Technical Report SL-8G-12, Report 3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Balsara, J. P., Albritton, G. E., Eagles, P. S., Graham, P. W., Johnson, W. G., Karagozian, J., Chen, P. H., Wanchoo, M. K., and Schumacher, J. U. April 1987. "Hard Silo Component Test Program; Core Dynamic Test 1 (HCDT-1)”, Technical Report SL-8G-12, Report 4, U.S. Army Engineer Waterways, Experiment Station, Vicksburg, MS.

Hammons, M. I., Albritton, G. E., Balsara, J. P., Karagozian, J., Chen, P. H., and Wanchoo, M. K. April 1987. "Hard Silo Component Test Program; Closure Dynamic Test 2 (CDT-2)”, Technical Report SL-86-12, Report 5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Graham, P. W., Balsara, J. P., Albritton, G. E., and Karagozian, J. September 1987. "Hard Silo Component Test Program; Headworks Dynamic Test 2 (HCDT-2)”, Technical Report SL-8G12, Report 6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Johnson, W. G., Balsara, J. P., Albritton, G. E., and' Karagozian, J. March 1987. "Hard Silo Component Test Program; Core Dynamic Test 3 (HCDT-3)”, Technical Report SL-86-12, Report 7, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hammons, M. I., Albritton, G. E., Balsara, J. P., Karagozian, J., Chen, P. H., Wanchoo, M. K., and Katyal, C. P. June 1987. "Hard Silo Component Test Program; Closure Dynamic Test 3 (CDT-3)”, Technical Report SL-86-12, Report 8, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Graham, P. W., Balsara, J. P., Albritton, G. E., and Karagozian, J. January 1987. "Hard Silo Component Test Program; Headworks Dynamic Test 4 (HCDT-4)”, Technical Report SL-86-12, Report 9, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hammons, M. I., Albritton, G. E., Balsara, J. P., Karagozian, J., Mould, J. C., Wanchoo, M. K., Katyal, C. P., and Levine, H. S. December 1986. "Hard Silo Component Test Program; Static Tests of Small-Scale Dome Closures," Technical Report SL-8G-12, Report 10, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Jones, P. S., Balsara, J. P., Albritton, G. E., Karagozian, J., Levine, H. S., Millavec, W. A., Wanchoo, M,. K., and Ness, D. December 1986. "Hard Silo Component Test Program;,Integrated

Component Silo Test 1 and 2 (ICST-1 and ICST-2), Vol 1 and 2,"Technical Report SL-86-12, Report 11, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS (SECRET).

Hammons, M. I., Albritton, G. E., Balsara, J. P., Karagozian, Wanchoo, M. K., and Levine H. S. March 1987. "Hard Silo Component Test Program; Dynamic Tests of Small-Scale Dome Closures CDT-3.5)", Technical Report SL-86-12, Report 12, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS (SECRET)

Hammons, M. I., Albritton, G. E., Balsara, J. P., and Karagozian, J. April 1987. "Hard Silo Component Test Program; Closure Dynamic Test 4 (CDT-4)”, Technical Report SL-86-12, Report 13, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS (SECRET).

Johnson, W. G., Albritton, G. E., Balsarat J. P., and Karagozian, J. June 1987. "Hard Silo Component Test Program; Core Dynamic Test 5 (HCDT-5)”, Technical Report SL-86-12, Report 14, U.S. Army Engineer Waterways Experiment Station, Vi-cksburg, MS (SECRET).

McDevitt, H. S., Albritton, G. E., Balsara, J. P. , and Karagozian, J. June 1987. "Hard Silo Component Test Program; Penetration Test A (PT-A)”, Technical Report SL-86-12, Report 15, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS (SECRET).

Eagles, P. S., Balsara, J. P., Windham, J. E., Karagozian, J., Tsai, W. T., Wanchoo, M. K., Walancius, J., Dickinson, M., Gran, J., and Wong, F. May 1987. "Hard Silo Component Test Program; Shear Friction Test 1 (SFT-1)”, Technical Report SL-86-12, Report 16, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS (SECRET).

Johnson, W. G., Albritton, G. E., Balsara, J. P., and Karagozian, J. March 1987. "Hard Silo Component Test Program; Core Dynamic Test 6 (HCDT-6)”, Technical Report SL-86-12, Report 17, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS (SECRET).

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Hammons, M. I., Balsara, J. P., Albritton, G. E., Karagozian, J., **Alpay**, J. R., Wanchoo, M. K., and Mould, J. C. May 1987. "Hard Silo Component Test Program; Closure Dynamic Test 5A (CDT5A)”, Technical Report SL-8G-12, Report 18, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS (SECRET).

Hammons, *M. I.*, Albritton, G. E., Balsaraj J. P., and Karagozian, J. April 1987. "Hard Silo Component Test Program; Closure Dynamic Test 6 (CDT-6)," Technical Report SL-86-12, Report 19, U.S. Army Engineer Waterways Experiment Station, Vicksburg, *MS* (SECRET).

Dove, R. C., Balsara, J. P., and Karagozian, J. May 1987. "Hard Silo Component Test Program; Core Dynamic Test 7 (HCDT-7)," Technical Report SL-86-12, Report 20, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hammons, M. I., Balsara, J. P., Albritton, G. E., and Karagozian, J. July 1984. "Hard Silo Component Test Program; Closure Dynamic Test 7A (CDT-7A)," Technical Report SL-86-12, Report 24, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS (SECRET).

Cost, V. T., Albritton, G. E., Balsara, J. P., and Karagozian, J. December 1986. "Hard Silo Component Test Program; Core Static,Tests 3, 4, 5, and 8 (CST 3, 4, 5, and 8)," Technical Report SL-86-12, Report 30, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

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